ISSN 0031-918X, The Physics of Metals and Metallography, 2013, Vol. 114, No. 1, pp. 27–32. © Pleiades Publishing, Ltd., 2013.
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STRUCTURE, PHASE TRANSFORMATIONS, AND DIFFUSION

Formation of Special Misorientations Related to Transition Bands in Structure of Deformed and Annealed Single Crystal (110)[001] of Fe–3% Si Alloy

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Received April 5, 2012

Abstract—A transition band between two deformation bands retains for the most part the orientation (110)[001] and shrinks to a thin interlayer or boundary with increasing degree of deformation. At a certain stage of deformation, the microvolumes that are arranged along the interface of the bands become adjusted to special misorientations. During primary recrystallization, cube-on-edge (Goss) grains, which grow from the transition band, have portions of special boundaries common with the deformed matrix; these boundaries were found earlier between the deformation bands. This indicates that the local domains with special misorientations formed at the stage of cold deformation transform during annealing into the corresponding primary-recrystallization nuclei.

Keywords: commercial Fe–3% Si alloy, single crystal (110)[001], cold deformation, deformation bands, transition bands, special misorientations, primary recrystallization

DOI: 10.1134/S0031918X13010067

INTRODUCTION

It is well known that the rolling of single crystals with an initial cube-on-edge (Goss) orientation (110)[001] leads to the formation of two symmetric octahedral orientations {112}⟨111⟩, and subsequent recrystallization annealing again results in the Goss orientation [1–5]. The structural transformations show that the hereditary mechanism of texture occurs in the material. The crystallographic analysis demonstrates that the precise Goss orientation is close to the special misorientations Σ9 and Σ27, which are multiples of three, relative to the symmetric octahedral orientations (it deflects from them at an angle of ±3.68° around axis ⟨110⟩) [6–8]. The latter fact allows us to suppose that the texture hereditary mechanism can be associated with special misorientations.

The primary recrystallization (PR) nuclei with the Goss orientation formed in the deformed Fe–3% Si alloy can originate in transition bands, shear bands, and Neumann bands (deformation twins) [1–5, 9–11]. It has been shown in works [10–12] that the formation of the nuclei of Goss grains at twins is accompanied by the appearance and evolution of special misorientations (Σ3 → Σ9 and Σ27) in the crystal mesostructure. The appearance of grains with the same orientation at different objects of the mesostructure during PR allows one to suppose the existence of a unified mechanism of the PR grain formation and relate it to special misorientations.

The role of special boundaries and, hence, special misorientations in the processes of texture formation that evolve during deformation and recrystallization remains the subject of the active attention of researchers [6, 10–15]. This work deals with the study of processes of the appearance of special misorientations during the formation of the deformation and transition bands and their role in the origination of PR nuclei.

MATERIAL AND EXPERIMENTAL METHODS

Test specimens were made of grain oriented electrical steel. They were shaped as plates 0.27 × 30 × 280 mm in size; the insulating coating was removed. Their structure consisted of coarse grains (the grain size in the rolling plane was 30–50 mm) with a rather perfect Goss texture {110}⟨001⟩. The specimens were rolled to a total reduction of 5–60% in the direction close to ⟨001⟩, after which they were subjected to gradient annealing in the temperature range of 400–800°C. The microstructure was examined at different stages of deformation and recrystallization using a JEOL JSM6490LV electron microscope equipped with an Oxford Instruments EBSD device.

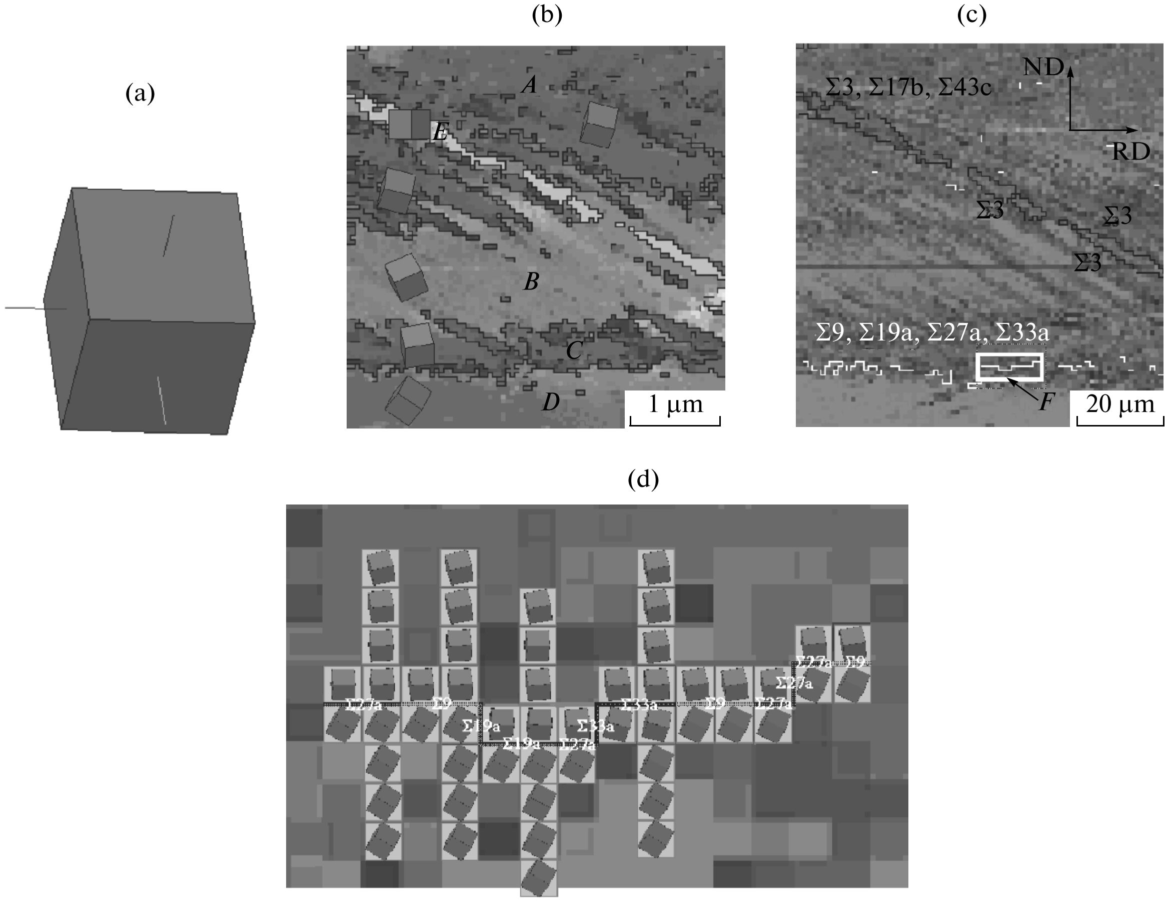

Fig. 1. Microstructure of single crystal of commercial Fe–3% Si alloy after cold rolling deformation by ~20%: (a) initial single crystal orientation in form of unit-cell projection; (b) orientation map with spatial image of unit cells; (c) special boundaries; (d) lattice orientations in vicinity of interface of deformation bands (domain **F** in “c” is magnified by 8.5 times).

To analyze the effective slip systems, we applied a laboratory coordinate system, the axes of which were related to the cold rolling direction (RD), the normal direction (ND) to the cold rolling plane, and the perpendicular direction (TD) to the above directions. The last direction coincides with the axis of the rollers and all three directions make up the right-handed vector triad. For a Goss single crystal, we have [001]‖RD, [110]‖ND, and$[\bar{1}10]$‖TD.

FORMATION OF DEFORMATION BANDS DURING COLD ROLLING OF SINGLE CRYSTALS

The mesostructure of the single crystals was examined at various degrees of deformation (Figs. 1 and 2). At already a relatively low deformation there is formed a fairly complex mesostructure which consists of twins that appeared at the initial stage of the process and sets of deformation and transition bands *A*, *B*, *C*, and *D* (Fig. 1b). All bands are distinguished by the orientations of the lattice from one another and, most importantly, from the initial orientation of the single crystal (Fig. 1a). In other words, the slip processes, which resulted in the rotation of the lattice about the TD and ND axes, occurred even in the bands whose orientation was relatively close to a Goss orientation (*A* and *C*). The mechanism of this reorientation of the crystal lattice (110)[001] somewhat deflected from the ideal orientation is presented in [16].

It is apparent that the formation of the deformation bands with the lattice that exhibits a tendency to one of two symmetric orientations from {111}⟨112⟩ is predetermined by the orientation instability of a Goss crystal rolled in the direction parallel to the crystallographic direction [001]. The cause of the formation of the set of deformation bands is the presence of local misorientations between the parts of the original single crystal. Various choices of the primary slip systems, the action of which governs the subsequent reorientation of the lattice, are implemented in different domains of the original single crystal lattice. It follows from this that the deformation bands differ in the rate of lattice reorientation.

The process of the interaction of the deformation bands is observed at the initial stage of their formation.

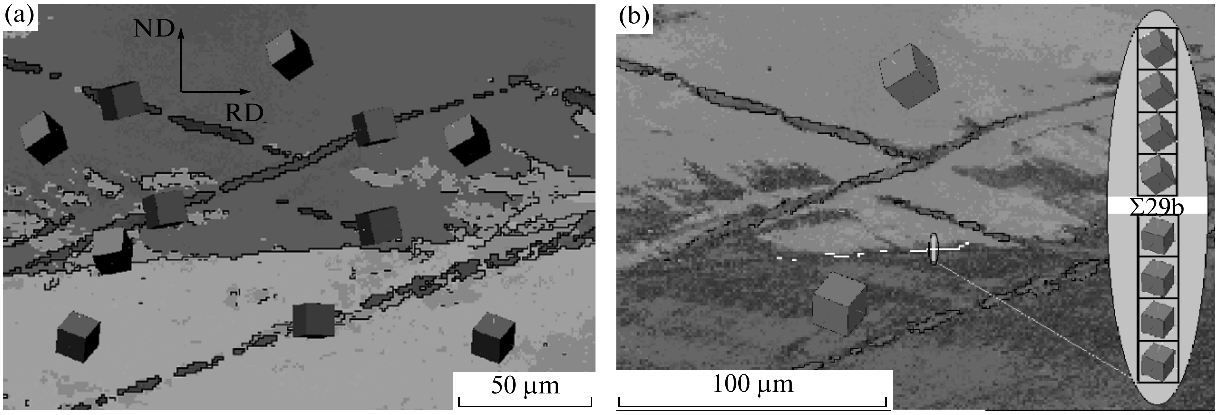

Fig. 2. Microstructure of a single crystal of commercial Fe–3% Si alloy after cold rolling deformation by ~60%: (a) orientation map with spatial image of unit cells; (b) special boundaries.

It is apparently related to the penetration of dislocations from some bands into the lattices of the other ones. The signs of this interaction can be seen in Fig. 1 as tongues located at the interfaces of bands *A* and *B*, as well as *B* and *C*.

Thus, we can assert that the domain (intermediate band) between two deformation bands with orientations close to {111}⟨112⟩ retains the orientation of the goss type due to the dynamic equilibrium of the opposite action of slip systems in different deformation bands. With increasing degree of deformation, the intermediate band shrinks to a thin transition band or boundary (Fig. 2a).

An interesting fact discovered in this study is the presence of special misorientations between the bands (*C* and *D*, Fig. 1). The special misorientations appear between the bands deflected mostly from each other, and are detected as portions of the special boundaries, which discontinue or transit from one to another. All special misorientations found (Σ9, Σ19a, Σ27a, and Σ33a) essentially make up one family of mutual orientations, which result from the rotation around the same axis $[\bar{1}10]$ to close angles (table).

The study of orientations of the lattice in the bands located along the special boundary (Fig. 1d) shows the absence of gradual transitions and the presence of fairly sharp transitions (up to 19°), which cannot be explained by the local lattice misorientations or the instrumental error. The adjustment of the lattices to the special orientation occurs from both sides of the boundary (in both bands). The orientations of near-boundary domains ~1–3 μm in size can differ noticeably from the basic (middle) orientation of the band. The closer the misorientations, the greater the probability of the transition from one misorientations to another (table).

Characteristics of special misorientations between deformation bands

Disorientation	Axis [*uvw*]	θ, deg	Relative frequency of occurrence	Transitions of misorientations		
				type	number	Δ of transition
Σ33a	110	20.05	0.6	Σ33a → Σ19a	6	–6.48
				Σ33a → Σ27a	3	–11.54
				Σ33a → Σ9	1	–18.89
Σ19a	110	26.53	1.0	Σ19a → Σ27a	11	–5.06
				Σ19a → Σ33a	6	6.48
				Σ19a → Σ9	2	–12.41
Σ27a	110	31.59	0.6	Σ27a → Σ19a	11	5.06
				Σ27a → Σ33a	3	11.54
				Σ27a → Σ9	6	–7.35
Σ9	110	38.94	0.3	Σ9 → Σ19a	2	12.41
				Σ9 → Σ27a	6	7.35
				Σ9 → Σ33a	1	18.89

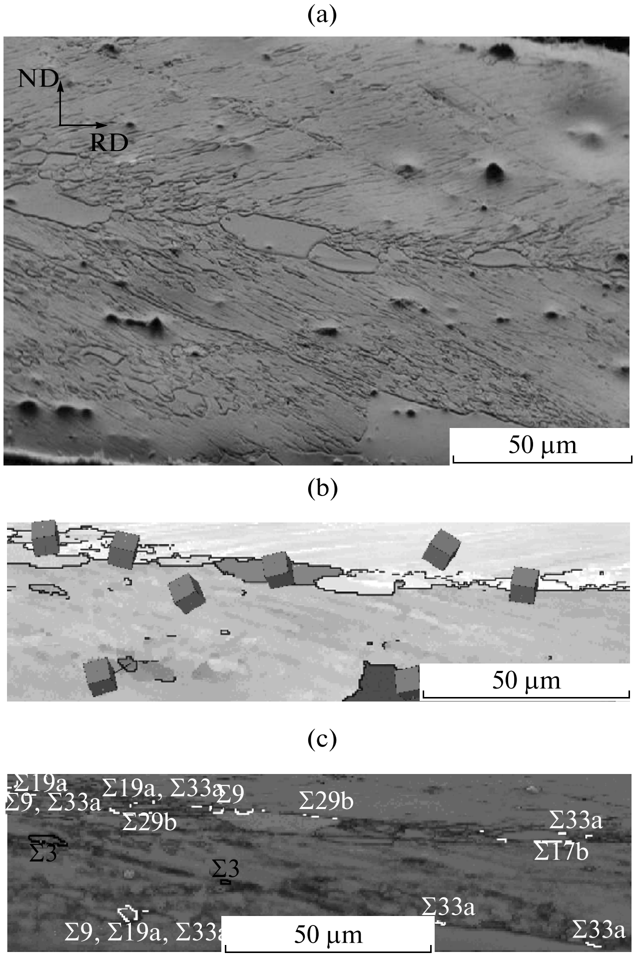

Fig. 3. Microstructure of a single crystal of commercial Fe–3% Si alloy at initial PR stage (ε ~ 50%): (a) reflection electron image; (b) orientation map with spatial image of unit cells; (c) special boundaries.

Taken together, the observed facts allow us to suppose that the appearance of special misorientations between the bands during deformation is a natural phenomenon that occurs at certain proportions between the orientations of crystal domains when a critical deformation degree is reached. The dislocation density is redistributed at the band interface so that domains with almost exact special misorientations are formed; they are energetically stable objects and are retained during subsequent deformation. We note that the appearance of the domain of special orientations can be a possible cause of the retention of the Goss orientation between deformation bands during deformation.

It is apparent that the approach of the crystal to the Goss orientation facilitates the formation of special misorientations during its deformation due to the rotation of the lattice around direction $[\bar{1}10]$. However, if the deflection of the original single crystal from orientation (110)[001] is fairly large and the bands acquire the orientations differing from {111}⟨112⟩ during deformation, the band interface also becomes the domain of the formation of special misorientations, although it is of the other type (Σ29b) (Fig. 2).

PRIMARY RECRYSTALLIZATION IN DEFORMED SINGLE CRYSTAL RELATED TO TRANSITION BANDS

The gradient annealing of the deformed specimen has resulted in different stages of PR. The totally recrystallized material has the predominantly Goss texture with a scatter over all angles.

The study of the initial recrystallization stage has shown that the PR nuclei with the orientations close to the Goss one appear mainly on deformation twins and shear bands. Transition bands were the dominant origins in some local domains with a low density of deformation twins and shear bands (Fig. 3a). At the initial PR stage, the growing grains are distinctly elongated along the transition band, which indicates the predominant direction of their growth (RD). A similar fact was also discovered during the formation of new grains at the deformation twin–matrix interface [11]. The process of the growth of a primarily recrystallized grain along the transition band or deformation twin can be considered to be the wetting of their special boundary, which in this case serves as the substrate for the origination and propagation of a new, perfect crystallite. These processes, which are related to the presence of special and small-angle boundaries, were observed during secondary recrystallization [17].

The grains that grow from the transition band during PR, most of which have the Goss orientation (Fig. 3b), have the portions of the special boundaries Σ9, Σ11, Σ19a, Σ27a, Σ33a, and Σ29b with a deformed matrix (Fig. 3c). These special boundaries coincide with the misorientations found previously between the deformation bands. This allows us to suppose that the nucleation of new grains during PR is related to the presence of portions of the special misorientations along the transition band.

It is important to note that the new growing grains, the nucleation of which is not related to transition bands, have the portions of special boundaries with the deformed matrix; the boundaries coincide with the special orientations discovered between deformation bands in the deformed state (Fig. 3).

The presence of the same special boundaries with the deformed matrix for grains that grow during recrystallization and appear at different objects of the mesostructure, such as deformation twins, transition bands, and shear bands, indicates the existence of a unified mechanism of the origination of PR nuclei. It is natural to suppose that this mechanism is the formation of special misorientations in the local domains of a crystal during deformation. The PR nuclei appear in these domains during subsequent annealing; they are in special misorientations with the nearest neighbors. The surfaces, which separate the PR nuclei from deformed objects of the mesostructure, can either contain portions of special boundaries or acquire them during recovery. The special boundaries formed in this way can have an advantage in mobility at recrystallization temperatures.

CONCLUSIONS

Different variants of the slip systems are realized in various domains of the lattice of a cube-on-edge (Goss) single crystal (110)[001] during cold rolling. These slip systems govern subsequent lattice reorientations and the formation of deformation bands. Deformation bands can differ in the rate of lattice reorientation. The domain between two deformation bands retains a Goss orientation (110)[001] due to the dynamic equilibrium of the opposite action of the slip systems in different deformation bands. With increasing degree of deformation, it shrinks to a thin transition band or boundary.

At a certain stage of deformation, local lattice domains are reoriented to definite angles and between the bands there appear zones that are in the special misorientations $\Sigma9$, $\Sigma19a$, $\Sigma27a$, and $\Sigma33a$. These special misorientations result from rotation at similar angles around the same axis $[\bar{1}10]$. The special misorientations domains are energetically stable objects retained during subsequent deformation.

During PR, Goss grains, which grow from the transition band, have parts of special boundaries with the deformed matrix. These boundaries coincide with the special misorientations found previously between the deformation bands.

The presence of the same special boundaries with the deformed matrix for the grains that grow during recrystallization and appear at different objects of the mesostructure indicates the existence of a unified mechanism of the origination of PR nuclei. It is natural to suppose that this mechanism is the formation of special misorientations in local domains of the crystal during deformation.

The role of special boundaries in the formation of secondary recrystallization nuclei is a widely debated topic [6–8, 13–15, 17], and no reliable experimental proof of the role of the special boundaries is found in anomalous-growth processes. The appearance of special misorientations should apparently precede the occurrence of special boundaries between alloy crystallites. In this work, we have experimentally shown the significant role of the special misorientations in the process of texture formation in commercial Fe–3% Si alloy during deformation and PR.

ACKNOWLEDGMENTS

The work was carried out at the facilities of the Laboratory of Structural Analysis Methods and Properties of Materials and Nanomaterials of the Shared Services Center of the Ural Federal University and supported by the Program of the Russian Academy of Sciences ("Structure" project) and the Federal Target Program of the Ministry of Education and Science of Russian Federation (project no. 02.740.11.0537).

REFERENCES

1. C. G. Dunn, "Cold-Rolled and Primary Recrystallization Textures in Cold-Rolled Single Crystals of Silicon Iron," Acta. Metall. **2**, 173–183 (1954).
2. H. Hu, "The Formation of (110)[001] Recrystallization Texture in Cold-Rolled and Annealed (110)[001] Crystal of Silicon–Iron," Acta Metall. **8**, 124–126 (1960).
3. T. Taoka, E. Furubayashi, and S. Takeuchi, "Formation of Cold-Rolled Texture and Recrystallized Texture in Single Crystals of 3% Silicon Iron. Part I," Trans. Iron Steel Inst. Jpn. **6**, 201–232 (1966).
4. T. Taoka, E. Furubayashi, and S. Takeuchi, "Formation of Cold-Rolled Texture and Recrystallized Texture in Single Crystals of 3% Silicon Iron. Part II," Trans. Nat. Res. Inst. Metals **9**, 187–207 (1967).
5. B. K. Sokolov, A. K. Sbitnev, V. V. Gubernatorov, I. V. Gervasyeva, and L. R. Vladimirov, "On the Influence of the Annealing Heating Rate on the Recrystallization Texture of a Deformed Single Crystal (110)[001] of 3% Silicon Iron," Textures Microstruct. **26–27**, 427–443 (1995).
6. G. M. Rusakov, A. A. Redikultsev, and M. L. Lobanov, "Formation Mechanism for Orientation Relationship between {110}⟨001⟩ and {111}⟨112⟩ Grains during Twinning in Fe–3% Si Alloy," Metall. Mater. Trans. A **39**, 2278–2280 (2008).
7. G. M. Rusakov, M. L. Lobanov, A. A. Redikultsev, and I. V. Kagan, "Model of {110}⟨001⟩ Texture Formation in Shear Bands during Cold Rolling of Fe–3% Si Alloy," Metall. Mater. Trans. A **40**, 1023–1025 (2009).
8. G. M. Rusakov, A. A. Redikul'tsev, I. V. Kagan, and M. L. Lobanov, "Mechanism of Formation of Shear Bands upon Cold Deformation of a Commercial Fe–3% Si Alloy," Phys. Met. Metallogr. **109**, 662–669 (2010).
9. B. K. Sokolov, V. V. Gubernatorov, I. V. Gervasyeva, A. K. Sbitnev, and L. R. Vladimirov, "The Deformation and Shear Bands in the Fe–3% Si Alloy," Textures Microstr. **32**, 21–39 (1999).
10. G. M. Rusakov, M. L. Lobanov, A. A. Redikul'tsev, and I. V. Kagan, "Specific Features of Cold Deformation of a (110)[001] Single Crystal of an Fe–3% Si–0.5 % Cu Alloy Related to Twinning," Phys. Met. Metallogr. **111**, 530–536 (2011).
11. M. L. Lobanov, G. M. Rusakov, A. A. Redikul'tsev, and I. V. Kagan, "Deformation-Twinning-Related Features of Primary Recrystallization of (110)[001] Single Crys-

tals of the Fe–3% Si–0.5 % Cu Alloy,” Phys. Met. Metallogr. **111**, 587–591 (2011).

12. G. M. Rusakov, M. L. Lobanov, A. A. Redikultsev, and I. V. Kagan, “Retention of the Twinning Σ3 Misorientation in the Process of Lattice Transformation during Cold Rolling of a Fe–3% Si Single Crystal,” Metall. Mater. Trans. A **42**, 1435–1438 (2011).
13. R. Shimizu, J. Harase, and D. J. Dingley, “Prediction of Secondary Recrystallization in Fe–3% Si by Three-Dimensional Texture Analysis,” Acta Mater. **38**, 973–978 (1990).
14. T. Kumano, T. Haratani, and Y. Ushigami, “The Relationship between Primary and Secondary Recrystallization Texture of Grain Oriented Silicon Steel,” ISIJ Int. **42**, 440–449 (2002).
15. H. Homma and B. Hutchinson, “Orientation Dependence of Secondary Recrystallization in Silicon–Iron,” Acta Mater. **51**, 3795–3805 (2003).
16. M. L. Lobanov, A. A. Redikul’tsev, G. M. Rusakov, I. V. Kagan, and O. V. Pervushina, “Effect of the Grain Orientation in the Material Used for the Preparation of an Ultrathin Electrical Steel on Its Texture and Magnetic Properties,” Phys. Met. Metallogr. **111**, 479–486 (2011).
17. H.-K. Park, J.-H. Kang, C.-S. Park, C.-H. Han, and N.-M. Hwang, “Pancake-Shaped Growth of Abnormally-Growing Goss Grains in Fe–3% Si Steel Approached by Solid-State Wetting,” Mater. Sci. Eng., A **528** 3228–3231 (2011).